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REVIEW

Speleoseismology: A critical perspective

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Abstract Speleoseismology is the investigation of earthquake records in caves. Traces can be seen in broken speleothems, growth anomalies in speleothems, cave sediment deformation structures, displacements along fractures and bedding plane slip, incasion (rock fall) and co-seismic fault displacements. Where earthquake origins can be proven, these traces constitute important archives of local and even regional earthquake activity. However, other processes that can generate the same or very similar deformation features have to be excluded before cave damage can be interpreted as earthquake induced. Most sensitive and therefore most valuable for the tracing of strong earthquake shocks in caves are long and slender speleothems, such as soda straws, and deposits of well-bedded, water-saturated silty sand infillings, particularly in caves close to the earth's surface. Less easily proven is a co-seismic origin of an incasion and other forms of cave damage. The loads and creep movements of sediment and ice fillings in caves can cause severe damage to speleothems which have been frequently misinterpreted as evidence of earthquakes. For the dating of events in geological archives, it is important to demonstrate that such events happened at approximately the same time, i.e. within the error bars of the dating methods. A robust earthquake explanation for cave damage can only be achieved by the adoption of appropriate methods of direct dating of deformation events in cave archives combined with correlation of events in other geological archives outside caves, such as the deformation of lake and flood-plain deposits, locations of rock falls and active fault displacements.

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Introduction

Broken speleothems are a frequent phenomenon in many caves. In the absence of clear relationships between observed damage and possible causes at the time of observation earthquakes seemed to be the most plausible explanation. The idea that earthquakes may cause damage in caves is, thus, probably as old as the idea that earthquakes are caused by cave collapse. Becker (1929) gives one of the first descriptions of cave damage possibly caused by an earthquake. However, not before the 1950s and 1960s did speleologists take again an interest in this research subject, particularly in Slovenia (Gospodarič, 1968; 1977) and in Germany (Schillat, 1965, 1976, 1977). In the 1980s and early 1990s, pioneering studies by Italian speleologists (Forti and Postpischl, 1984; Postpischl et al., 1991) attracted much interest amongst Earth scientists not particularly involved in karst and cave research. Since then speleoseismology, i.e the investigation of traces of earthquakes in caves, has gathered momentum in those European countries most likely to have historic and prehistoric strong earthquake archives (Delaby, 2001; Forti, 2001; Gilli, 1995a, 1996; 2004; Gilli et al., 1999; Lemeille et al., 1999).

In recent years speleology has made significant progress in the understanding of processes that cause damage in caves. With this improved knowledge, many observations originally thought to be caused by earthquakes are presently attributed to non-seismic processes (Gilli, 1999, 2004; Kempe and Henschel, 2004). What ever the reasons are for the observed damage, the fundamental problem clearly addressed by Forti and Postpischl (1984) still remains: "The geological, morphological and speleogenetic analyses can be useful in distinguishing the various types of collapses that may be present in caves, even if such analyses will never be able to give a definitive certainty as to their cause". Following earthquake research practice, it is possible to overcome such uncertainties using an approach called 'integrated paleoseismology' (Becker et al., 2005), based on studies of traces of strong historic and prehistoric earthquakes in different geological archives, including cave archives. Applied on a regional scale, the comparison of the results from the different geological archives may compensate for the short-comings of individual archives, improving the reliability of the interpretations of the data. Caves themselves are already multi-archives to which the concept of 'integrated paleoseismology' can be applied. In this work we present a critical review of key aspects of speleoseismology and concepts arising from multidisciplinary paleoseismological studies in Switzerland and elsewhere.

Eye-witness accounts of earthquake effects

The direct approach to study the effects of earthquakes in caves is the evaluation of eye-witness accounts. Fortunately, it rarely happens that speleologists are in caves just at the time of strong earthquake shocks. However, the few well documented observations and an internet inquiry amongst cavers (Gilli and Delange, 2001) supply vital information. In most cases nothing is felt and speleologists are sometimes very surprised to hear that during their stay in a cave a strong earthquake occurred (Audra, 1999; Renault, 1970). In some cases speleologists heard unusual noises: (1) a "thunderbolt" in the Buddha cave, Grand Canyon, during the M 5.2 Flagstaff earthquake, Arizona, in 1952, and (2) the same sound in a cave in Papua New Guinea during a M 5.1 earthquake (Audra, 1999). (3) a noise similar to a "Boing 747 jet engine" in the Church cave, Kings Canyon National Park, Sierra Nevada, during a M 5.5 earthquake in 1974, and (4) a "howling as from a wounded animal" in the Frasassi cave in Umbria, Italy, during the M 5.6 Assisi earthquake of 26th September, 1997. Most frightening was probably the experience of a caver who was trying to pass through a narrow shaft in the Churchill cave (USA) in autumn 1974 when the cave was struck by an M 5 earthquake. The caver felt something like a "vibro-massage". On May 22nd, 1995 in Dimnice cave, Slovenia, cavers felt a M 4.0–4.2 earthquake at an epicentral distance of 20–30 km. Although this earthquake did not trigger any damage or rock falls in the cave, they felt the ground shaking, an air blow, heard a noise and could see fluctuations in water levels (zumer, 1996). During the M 4.9 Bovec earthquake of July 12th, 2004 in Slovenia, a guide in Postojna cave heard a noise "similar to a by-passing train, coming closer and becoming louder and after passing disappearing" (S. šebela, pers., comm., 2005). The only observations of cave collapse and severe damage known to the authors come from the Shepran cave, Bulgaria during the M_S 7.0 Chirpan earthquake of 1928, about 55 km SW of the epicentre (Kostov, 2002).

Post-earthquake damage observations

There are only a few published cases of observations from caves visited immediately after an earthquake. In general, changes have not been reported, even in cases of strong earthquakes and for caves close to an epicentre, e.g. Nojima-do cave on the isle of Awaji-shima near the fault-rupture that caused the 1995 M_S 7.2 Kobe earthquake in Japan (Gilli and Delange, 2001). The M 6.8 Arette earthquake in France in 1967 scaled-off rock fragments from the walls of several caves in the region (Renault, 1970). A 1 m $\times$ 0.5 m rock slab came down in Wiburds Lake cave, Australia, at May 20th, 1995, probably triggered by the nearby Jenolan earthquake. Beside this block failure, no further damage could be observed in the cave on the day after the earthquake. Important examples of limited damage are the well documented observations from the Barrenc du Paradet cave near Saint-Paul-de-Fenouillet, southern France (Gilli et al., 1999) where on February 18th, 1996, a M 5.2 earthquake, with a felt radius of 150 km, occurred within an area with caves. Eight caves were investigated within a radius of 2 to 10 km around the epicentre. Only the most elevated cave, the Barrenc du Paradet cave at an altitude of 840 m a.s.l., showed significant damage, with many broken soda straws covering parts of the cave floor and small rock shards from the cave's walls and ceiling.

Earthquake effects on underground cavities

In common with the experiences of speleologists, miners and tunnellers are often surprised to learn that a damaging earthquake had taken place whilst they were underground. The examples of damage and movements observed in caves described in the preceding sections establish the veracity of the general assumption that natural crustal earthquakes can cause characteristic damage in caves. They also serve to illustrate the complexity of the possible relationships with impacting earthquake strong motions. Because there are few clear patterns and correlations in the cave observations, it would appear that comparisons with the observed effects of earthquake-induced movements in engineered underground spaces would be profitable. In reality, the most of the damage to sub-surface engineered cavities is to the man-made components such as tunnel linings and then only, as a rule, to those at shallow depths.

The extensive lifeline-damage studies following the great Alaska earthquake of 1964 document many examples of wide ranging damage; however, deep mines and even railroad tunnels in bedrock were virtually undamaged. Wang (1985) reports the distribution of damage to the coal mines at Tang-Shan in China that occurred during the great 1976 earthquake (M 7.8). He reports that damage decreased down to a depth of 500 m and that the distribution of the damage suggests that the attenuation of shaking away from the Tang-Shan fault zone is greater than at the Earth's surface. Dowding and Rozen (1978) reviewed the lessons of 71 rock tunnel damage case histories from California, Alaska and Japan. The tunnels serve water and rail links, have a diameter of 3 to 6 m, and damage can be compared with that which occurred at the surface. Dowding and Rozen (1978) found that tunnel collapse is rare and occurs only in extreme conditions. Although it is difficult to establish wall-rock damage in lined sections, they suggested that both unlined and lined tunnels experienced no damage beneath surface areas with up to 0.19 g (horizontal) acceleration. Minor damage increased up to 0.4 g and only when surface accelerations exceeded 0.5 g was there consistent collapse due to shaking alone. Whilst valuable as generalizations, these observations lack clear correlation with depth although deeper tunnels appear to experience less damage. More useful data on the role of depth have been reported by Shimizu et al. (1996), based on their studies of the distant earthquake strong motion vibrations monitored in the underground test facility at the Kamaishi Mine in Japan. They show that accelerations at 650 m and 150 m below ground are in the range of 50–25% and 100–50% of the surface value, respectively. The surrounding rocks are those of plutonic igneous granodiorite types, mineralized and fractured in an east-west direction. The accelerations produced by over 200 earthquakes have been observed over the period 1990–1994, and their detailed comparison of the values from 41 main events captured by both vertical and horizontal component instruments at 4 levels reveal that the observed decreases in acceleration with depth are similar for all three components but the maximum values recorded were in the E-W direction. A number of very large earthquakes (M 8.1, M 7.8) at distances of several hundred kilometres produced low accelerations at the mine, whereas the greatest accelerations were produced by two earthquakes of M 5.9 and M 5.3 at hypocentral distances of 50–100 km. None of the accelerations exceeded 0.1 g.

The experiences documented for engineered caverns and chambers reveal further information. In general, these openings are an order of magnitude greater in size and generally deeper than tunnels. Apart from soft ground tunnels, most underground excavations are in 'rock', ranging from weaker weathered to stronger unweathered rocks. The type of rock influences the attenuation of seismic waves and at the depths of deep mines and caverns discontinuities are important, particularly jointing and faulting. Dowding et al. (1983) use a form of distinct and finite element modelling ('hybrid block model') to estimate the effects of frequency and jointing for seven cases of cavern response to vertically propagating shear waves of wavelengths 1, 2 and 8 times the cavern height. They found that near cavern blocks slide during periods of low normal stress and that a wavelength twice the cavern height produces the greatest displacements. The scenario for the most informative case (Case 1: depth of 600 m and a maximum velocity of 30.0 ms^{-1}) predicted a displacement of 47 mm at the maximum assumed frequency of 10 Hz.

Most of the severe damage and collapse of hard rock tunnels appear to be limited to sections which cross fault zones. Amongst the many reports of such damage, the best known are the near-fault failures and alignment deflections of the Wright-1 tunnel during the great 1906 San Fransisco earthquake and the cracking of the Tanna tunnel associated with large amounts of fault slip during the 1930 Idu earthquake in Japan. More recently, much attention has been focused on the severe damage of the twin Bolu tunnels in Turkey during the devastating 1999 Duzce M 7.2 earthquake. Although at the time these road tunnels were being constructed through the fault zone of the Bakacak fault, which is part of the highly active North Anatolian Fault System, the damage seems to be related more to severe shaking of the clay gouge material rather than fault movement. Where the fault rocks occur as narrow shear zones in tunnels and caves, they should be considered to be possible locations of large rapid displacements having the potential to change the orientation/shape of the cave and cause extensive block falls. Such a fault may be not only active but capable of generating earthquakes. Even small events close to the cave could create near-field shaking comparable to explosions (McGarr, 1983; Labreche, 1983).

The above observations suggest that for cave systems in strong thickly bedded slightly jointed limestones at distances of perhaps 150 m below the ground surface, damage to walls and roofs are unlikely to take place except in cases of a very large shallow earthquake not far away. In this case, accelerations and velocities of strong motion could be capable of dislodging rock wedges and rotating and loosening blocks. Such block movements could break speleothems. Although evidence of frequency – and wave length-related damage in caves and to tunnels/caverns is rare, engineering studies have often assumed relationships for the purposes of engineering design. Further amplification of motions could be possible where the incoming waves have appropriate length to opening ratios. Selective frequency-dependent damage in an otherwise undamaged cave may be seen in fragile/vulnerable cave ornaments and deposits such as soda straws and soft sediments. Although the levels of shaking underground are generally lower than those at the surface, extensive selective damage is to be expected from the much greater energy at the higher frequencies for short durations that are possible when the vulnerable cave structures are close to a co-seismic rupture on a fault i.e. in the near field. It seems that both displacements and shaking due to nearby co-seismic rupture and more distant large earthquakes should be considered in the investigation of the causes of fractures and failures of "massive" speleothems. The effects of the long period long duration low acceleration motions of greater more distant earthquakes are considered to be limited to breaks in long slender speleothems with low natural frequencies (Lacave et al., 2003).

Because older caves are often within the higher slopes of valleys, the earthquake engineering evidence that surface ground motion amplification is associated with topography needs to be considered (Davenport, 1998). During the 1971 San Fernando Valley earthquake in California, there was extensive surface damage to structures and landslides. At the Pacoima Dam site, strong motion records revealed that very high accelerations occurred high on slopes, namely a peak ground acceleration of 1.17 g (Reimer et al., 1973). The instrument was located on a steep ridge of the valley and it is suspected that some of the very high motion may be associated with cracking of the rock beneath the site. Such considerations have been built into scenarios which suggest that valley floor acceleration of 0.25 g (which is expected from not to distant large to modest earthquakes) could be amplified twice or three times on slopes. Although such high accelerations would reduce rapidly with distance into the hillsides, the potential for damage to caves systems in topographically exposed positions at a shallow depth is increased (Gilli and Delange, 2001). Such a situation seems to have occurred in SW France where only the most elevated cave was damaged during the Saint-Paul-de-Fenouillet earthquake (Gilli et al., 1999; 2004).

Broken speleothems and growth anomalies

In situ-observations

The investigation of broken speleothems (Fig. 1), so-called seismothems, and speleothem growth anomalies (Fig. 2) can be considered as the 'classical approach' to speleoseismology (Delaby, 2001; Forti and Postpischl, 1981; Forti, 2001; Kagan et al., 2005; Moser and Geyer, 1979; Postpischl et al., 1991; Schillat, 1965; 1976; 1977). From the pioneering work of Schillat (1965–77) developed by Forti and Postpischl (1981–91), speleothems – stalagmites, stalactites and soda straws – are considered to be the main diagnostic components for the cave archive, being abundant and easily accessible in well-decorated caves. Stalagmite investigations have been particularly successful for three main reasons: (i) the thick horizontally-bedded layers in the central part of the stalagmite can be sampled easily, facilitating dating, (ii) if the positions of the drip points on the ceiling remains stationary, tilting of the cave's floor can be recorded by changes in the growth directions ('growth anomalies') (Fig. 2) (Forti, 2001; Forti and Postpischl, 1984; Schillat 1976, 1977), (iii) when stalagmites break during an earthquake, the fallen parts may remain close to the stump where the floor is flat. If the relationships between the fallen parts and the stumps allow the reconstruction of the original speleothems, estimates of the direction of the earthquake source may be possible (Delaby, 2001; Kagan et al., 2005; Moser and Geyer, 1979; Postpischl and Forti, 1991). Estimates of the ages of damaging events can be obtained by dating the oldest layer at the base of the regrowth and the youngest layer at the tip of the stalagmite fragment (Fig. 1d (1, 2)) (Forti, 2001; Kagan et al., 2005; Postpischl and Forti, 1991).

More recently, stalactites, and particularly soda-straws, have become increasingly more interesting in speleoseismology (Gilli, 1999; Gilli et al., 1999; Kagan et al., 2005). This interest was stimulated mainly by results of *in situ* and laboratory experiments, indicating that most speleothem morphologies are stable and are difficult to break during earthquake shaking (Cadorin et al., 2001; Lacave et al., 2000, 2004). However, the most fragile speleothems, particularly soda straws, appear to be vulnerable and could be amongst the best indicators of the earthquake history of a cave. Because they are difficult to date directly, Gilli (1999b) suggests dating the deposit in which the broken soda straws are embedded (Fig. 3). Flowstone layers in which broken soda straws are concentrated are considered to be best.

Growth anomalies of speleothems in seismically active areas such as Italy or Central America (Forti and Postpischl, 1984; Gilli, 1996, 1997; Postpischl and Forti, 1991) are being interpreted as evidence of strong earthquakes associated with regional uplift and tilting of the Earth's crust and local fault-bounded block movements (Forti and Postpischl, 1980, 1984). Growth anomalies are not necessarily restricted to changes in growth directions of a stalagmite: they can also be changes in the texture, colour and chemical composition of stalagmite layers (Forti, 2001). Such growth anomalies may be the only indicators in deeper caves, whereas in caves closer to the Earth's surface and particularly those in a topographically-exposed position, speleothem damage could be the dominant indicator for strong earthquake shocks (Gilli, 1999, 2004). However, even in the case of strong earthquakes, the percentage of damaged to un-damaged speleothems appears to be generally small. Gilli (2004) notes that, in the Barrenc du Paradet cave in France damage related to the 1996 St-Paul-de-Fenouillet earthquake was mainly restricted to soda straws of which less than 2% failed. The explanation for this surprising observation is provided by the results of the experiments and modelling discussed below.

Experimental and theoretical approaches

The general objective of such investigations has been to establish quantitative relationships between the observations of broken and unbroken speleothems and natural earthquake motions. The basic questions which arise include: Can earthquakes break speleothems? If so, is it possible to quantify the "strength" of such earthquake motions? What are the uncertainties in such quantifications? Finally, can unbroken speleothems define an upper limit of "strength" for earthquakes occurring

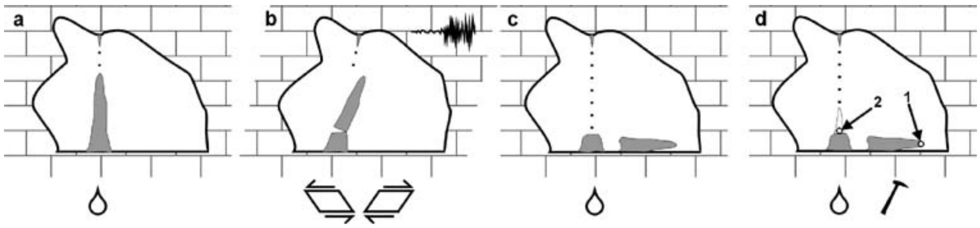

Fig. 1 Example for the use of broken stalagmites in speleoseismology. (a) An active stalagmite may (b) break by strong earthquake shocks. If (c) the dripping point at the ceiling will not change its position after the earthquake, (d) a stalagmite regrowth will develop on top of the stump. Samples taken from the tip of the broken stalagmite (1) and the base of the regrowth (2) will pre- and post-date the event respectively

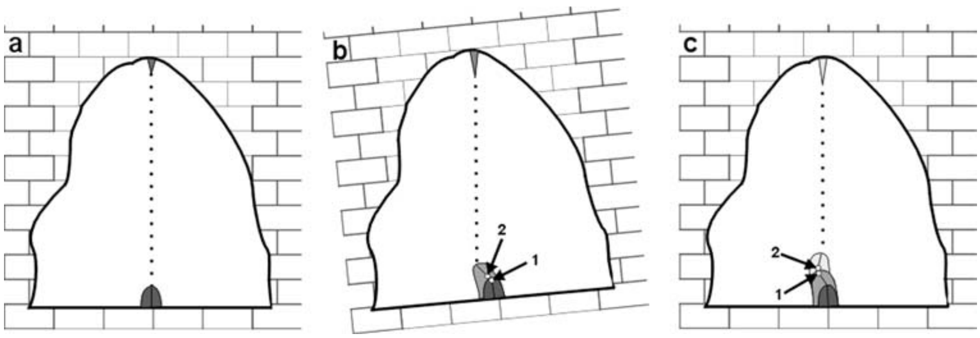

Fig. 2 Scheme showing the development of growth anomalies of a stalagmite caused by tilting of the cave's floor (after Forti and Postpischl, 1984; Schillat, 1976, 1977). Such growth anomalies may be generated by sudden large-scale tectonic movements or local slope instabilities, unless changes in the position of the dripping point and in airflow intensity and direction have occurred due to other causes. Sampling sites, which pre- and post-date the tilting event, are indicated (respectively, 1 and 2)

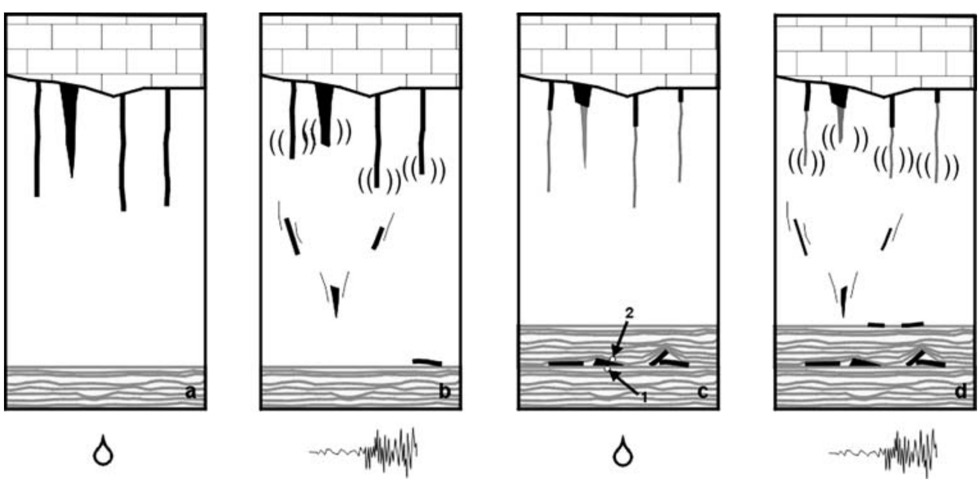

Fig. 3 In a well-decorated cave with ongoing flow stone development at the cave floor (a), an earthquake may cause the rupture of some stalactites and soda straws (b), fragments of which will be embedded in the sediment whilst regrowth is forming on the stalactite stumps (c). The next damaging earthquake will repeat this process (d). By dating the flowstones below (1in (c)) and above the layer of broken speleothems (2 in (c)), a chronology of strong prehistoric earthquakes may be established (modified after Gilli, 1999b)

during the speleothems' life time? Many reports that interpret broken speleothems (soda straws, stalactites and stalagmites) as indicators of past earthquakes can be found in the literature. A concise overview of what has been published so far is given in Forti (1997, 1998). Most of these publications are purely descriptive from a mechanical point of view. The first investigations undertaken on the mechanical behaviour of speleothems were those of Henne (1972) and of Pielsticker (1982). Both of them present results of modelling that lead to conclusions pointing in the same direction as the study of Lacave et al. (2004). Interestingly, although their modelling is less refined, their work virtually excludes earthquakes as a possible cause for speleothems' rupture, except for very local events. In particular, the modelling does not consider weaker sections along the speleothems caused by changes in the growth rates and also in chemical composition, which preferentially fail under dynamic loading and are not restricted to their basal sections as proposed by Henne (1972) and Pielsticker (1982). Later efforts by Gilli et al. (1999). attempted the quantification of the mechanical behaviour of speleothems during earthquake loading. They conclude that damages due to a magnitude 5.2 earthquake in the epicentral area are limited to some broken soda-straw. Other damages to large rocks or speleothems could only be attributed to an older major earthquake with an activation of the cave fault. Cadorin et al. (2001) performed static and dynamic bending tests on four broken stalagmites of the Hotton cave in Belgium in order to determine the calcite rupture stress. The obtained peak ground accelerations needed to break the investigated speleothems are much higher than accelerations commonly expected during earthquake shaking. This is mainly due to the fact that they did not take into account weaknesses due to structural anomalies along the speleothem.

Lacave et al. (2004) investigated the mechanical behaviour of speleothems through static bending tests in the laboratory performed on stalactites and soda straws, resulting in a probability density function for the rupture bending stress. A statistical approach is mandatory, because it is the variation of the mean tensile resistance that makes it difficult to estimate the acceleration necessary to break an individual speleothem. Additionally, *in situ* measurements in order to determine the range of fundamental natural frequencies and structural damping characteristics of these speleothems were carried out (Lacave et al., 2000). It appears that only long and thin speleothems have natural frequencies within the range of seismic excitation, i.e. <30 Hz (Fig. 4). Accordingly, during seismic motion, most speleothems would not experience dynamic amplification, but would move with their base as a rigid structure. However, those having natural frequencies within the seismic range may undergo significant dynamic amplification of 4 or 5 times, due to extremely low structural damping of the order of only 0.1% of critical damping.

Lacave et al. (2004) used numerical modelling techniques to investigate the dynamic behaviour of stalactites and soda straws as a succession of truncated cones to allow for geometrical irregularities and uncertainties (Fig. 5). The assumption of rigid stalactites with homogeneous resistance was tested and later abandoned when it became clear that stalactite deformation, with the possibility of dynamic amplification, has to be taken into account. Homogeneous cylinders would break at their base, but in the material tests only a few stalactites were seen to break at their base. This implies a need to account for the possibility of a stalactite to break at any section of possible weakness, requiring the modelling of the material resistance heterogeneity along the stalactites. Finally, Lacave et al. (2004) calculated "vulnerability" curves for stalactites, being the probability of breaking as a function of peak ground acceleration (PGA).

Based on the experiments and modelling of Lacave et al. (2004). it can be concluded that only the long and slender speleothems are vulnerable to damage during a "reasonably" strong earthquake, i.e. with 3 m/s^2 $<$ PGA $<$10 m/s^2. These are soda straws at least 40 cm long, thin stalactites with a diameter of about 2 cm and a length of at least 60 cm, stalactites and stalagmites with a diameter of 5 cm and a length of at least 1 m or stalactites and stalagmites with a diameter of 10 cm and a length of at least 1.5 m. Speleothem vulnerability can be explained as follows: (1) the longer the speleothem the greater the bending moment, and the smaller the diameter, the higher the maximum tensile bending stress for a given bending moment; (2) sufficiently long and slender speleothems have their fundamental natural frequencies within the frequency range of seismic excitation; and (3) the probability of a speleothem containing a weak section, i.e. an internal structural irregularity with a lowered rupture stress, will increase with increasing length of the speleothem. In contrast to long and slender speleothems most stalactites (and stalagmites) should resist fracture during realistic earthquake loading, i.e. with PGA $<$ 10 m/s^2. Nevertheless, the assumed unbroken shape of many broken stalactites seen in caves indicates a low or very low seismic vulnerability, suggesting that the majority of them may not have failed as a direct consequence of earthquake ground shaking.

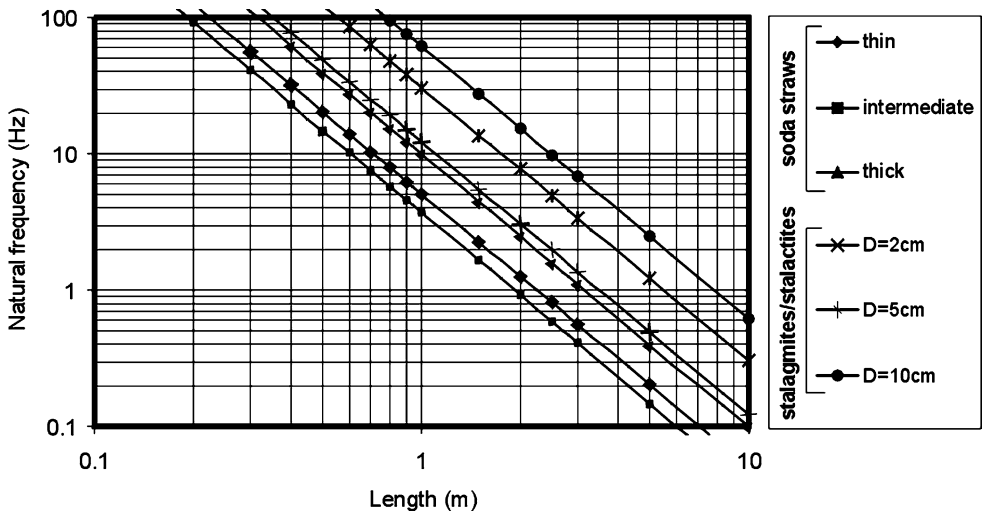

Fig. 4 Estimated natural frequency versus length for a range of speleothem types (soda straw, stalactite, stalagmite) (modified after Lacave et al., 2004)

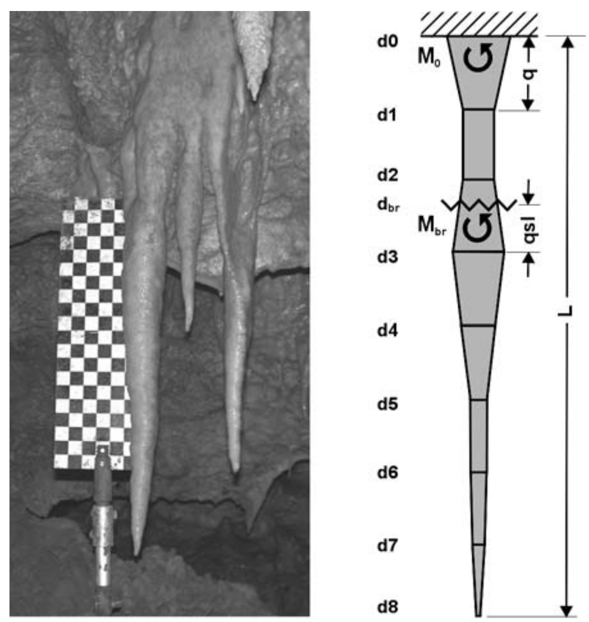

Fig. 5 Left : photograph of natural stalactites with scale board (each square equals 20 mm × 20 mm); right: geometry of a stalactite of length L modelled as a succession of truncated cones with equal height q, where M_0 is the maximum bending moment at the base section, M_{br} is the bending moment where the stalactite will break based on the geometry and load, and qsl is the height of the broken cone segment after failure measured between the base of the k-th truncated cone and the breakline (modified after Lacave et al., 2004)

Alternative explanations

Anthropogenic causes

The difficulties in proving a coseismic origin for damage to large speleothems requires consideration of alternatives explanations. Most of the damage could be the result of the actions of humans. An anthropogenic origin is frequent in areas where people use to visit caves, for shelter, worship, tourism, spelunking, mining or exploration. In the Dograrati cave (Kefalonia, Greece) the stalactites were broken by gun fire during WW2. In most of the caves around the famous Carlsbad National Park Cavern in the USA, speleothems were collected for sale to tourists at the beginning of the XXth century. The 'more common action of man' can be identified for instance by deep impact marks and fractures oblique to the growth axes of speleothems (Crispim, 1999). Such damage can be very old, as in the cave of Bruniquel in France where an underground camp was built 50'000 years ago using broken speleothems (Rouzaud et al., 1995).

The quarrying of rock may cause damage in caves close to the surface due to the use of explosives and due to vibrations caused by heavy vehicles (Crispim, 1999). However, as many examples show, this effect rapidly decreases with increasing distance and depth, so that even at a few decametres, perfectly preserved cave sections can be seen (Knolle, 1982; Pielsticker, 1998). This is to be expected because rock blasting generates the predominantly high frequencies which are generally damaging for speleothems but rapidly attenuate with increasing distance. The distance within which damage occurs is a function of the characteristics of the speleothems, the surrounding rock, and the frequency content of the sources. Lacave et al. (2003). suggest that rock blasting using several kilograms of explosives may be expected to cause damage to speleothems only within a distance of 50 to 100 m.

Erosion and soil creep

The most common natural causes that may affect the substratum of speleothems are subsurface erosion and differential subsidence. If a stalagmite or a column becomes too heavy, compaction or failure of the soil foundation may cause settling and rupture (Gilli, 1986, 2004). In addition, water circulation may erode the sediment underneath a stalagmite causing collapse (Kempe, 1989; Knolle, 1982). Another mechanism was observed in Ribière cave (France) where stalactites are embedded in karst sediments that totally fill several parts of the cave. Here, creeping of the sediments caused the stalactite formations to break (Gilli, 1999a, 2004). Sometimes the fine-grained sediments can be washed out and the speleothem fragments are transported, oriented and deposited a few meters away from their previous position.

The former infill of caves with sediments can often be deduced by various observations: (1) relics of cave sediments in niches, (2) corrosively widened traces of fractures in the ceiling (Fig. 6a), (3) paragenesis channels, indicating corrosion at the cave's ceiling due to progressive sediment infill of the conduit, (4) broken speleothems or blocks in presently unusual positions (Fig. 7a, 6c–e), (5) speleothem debris attached to the wall or other speleothems above the present cave floor (Fig. 6c,d), (6) stalactites with broken off tips (Fig. 6b, 7b), (7) long broken soda straws on a rocky cave floor or (8) in case of massive columns that resisted the sediment creep, broken speleothems on the flow facing side but intact speleothems in the 'flow shadow' (Fig. 8).

Underground glaciers and ice creep

As caves usually keep traces of their previous fillings, it is possible to understand the origin of the breaks, but ice is a kind of cave filling that leaves almost no traces. In periglacial environments or in regions with cold winter seasons, ice can be generated in caves by the transformation of snow to ice in shafts or in static and dynamic ice caves, respectively, by freezing drip water. Both processes may form glaciers in caves that cover speleothems. The actions of an existing glacier are visible in Snezna cave (Slovenia) (Gilli, 2004) and older signs have been described from many caves, for instance in Barrenc du Paradet cave, France, (Gilli, 2004), in Postojna cave, Slovenia, (Kempe and Henschel, 2004) and in Grosse Sundern cave, Germany (Pielsticker, 1998). Under the weight of the ice, flowstones can break (Fig. 7a) and the movement of glacier ice may break the embedded speleothems and may shear off coatings from the cave walls (Fig. 8) (Gilli, 2004). Large columns can be broken during small, even insignificant, displacements (Figs. 7a, 8) (Kempe and Henschel, 2004; Spöcker, 1981). Smaller speleothems, fragments of flowstone and rocks from the ceiling and the wall of a cave may be transported sometimes for considerable distances, and may form underground moraines (Fig. 7c). In ice embedded and transported blocks may even scratch the walls of the cave causing typical striations (Pielsticker, 1998). When the ice melts, the cold water dissolves those parts of the speleothems and rock surfaces, which are no longer included in the ice (Fig. 7d) (Gilli, 2004). When the glacier has totally disappeared the fragments left on the soil keep the orientation created by the movement of the ice (Fig. 8). Such oriented features will be misleading, if they are regarded as evidence for a coseismic origin and alternative explanations are not considered. For instance in the Geisloch cave in Germany subsidence in flowstones, broken flowstones, dissolved stalagmites and underground moraines suggest that most of the breaks previously attributed to earthquakes (Moser and Geyer, 1979) are more likely to have been caused by ice filling (Kempe, 1989; Spöcker, 1981).

Finally it should be mentioned that large inland glaciers have also a regional geological effect. The weight of the ice during glacial stages can induce

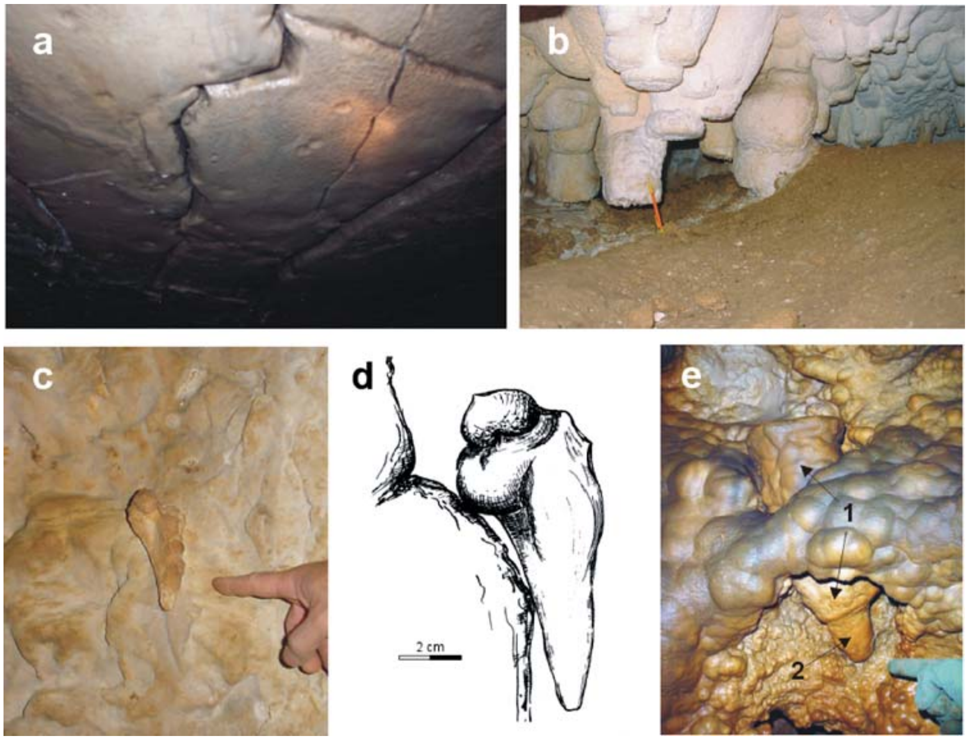

Fig. 6 (a) Corrosion-widened fracture traces at the ceiling of Erdmanns cave, Germany, (b) stalactite stumps in St. Brais 3 cave (Switzerland) coated with moonmilk and still partly embedded in clastic cave deposits, (c) cave wall with cemented speleothem fragment in Geisloch cave (Germany), (d) the same fragment as drawn by Spöcker (1981), illustrating 'Eisanhaftung' (ice adhesion), which was probably brought by ice into its position at the wall and kept in this position for long enough to be fixed by 'sinter' formation, (e) probably a stalagmite stump [1] with a small regrowth on its tip [2] trapped and held upside-down in a niche in the cave wall and later partly covered with 'sinter', Zoolithen cave, Germany.

glacioisostasy and glaciotectonics particularly during late- or post-glacial stages, when crustal rebound can provoke movements along faults and cracks and can trigger strong earthquakes (Davenport et al., 1989; Fjeldskaar et al., 2000; Mörner et al., 2000). Many of the Swedish caves in Precambrian bedrocks are caused by huge rock bursts shortly after the retreat of the glaciers, such as the 2 km long, labyrinthic Boda cave (Sjöberg, 1987). Earthquakes associated with crustal rebound should also have an impact on pre-existing caves in carbonate rocks.

Floods, mud and debris flows

Speleothems broken by floods have been reported in the Siebenhengste Cave system (Funcken and Decannière, 1988; Wildberger and Preiswerk, 1997). In July 1987 the deep part of the system was hit by a one thousand year flood. Many fossil conduits have been reactivated, opening some new passages for the cavers and closing others. Boulder chokes moved and several speleothems, including thick and tall ones, have been broken. In the Achama Lécia cave in the Pyrenees, a devastating debris flow containing mud and pebbles killed a caver in 1988 (Gilli, 2004). Prehistoric examples for such mud flows are seen in the French caves of Azeleguy (Vanara, 1997) and Pierre Saint Martin (Maire, 1990). Such devastating mud and debris flows are normally related to a sudden outburst of tremendous amounts of water, for instance due to the sudden drainage of a lake into a karst system or due to the break of a temporarily blocked drainage system during a period of long-lasting rainfall.

Remnants of debris flow deposits in caves can be easily recognized by their chaotic texture with virtually no layering, a low degree of grading and matrix-supported coarse components. Frequently, some of the coarse components are broken speleothems (Gilli, 2004). Such debris flows cause large-scale damage in caves, particularly to speleothem decoration. Floods with a low

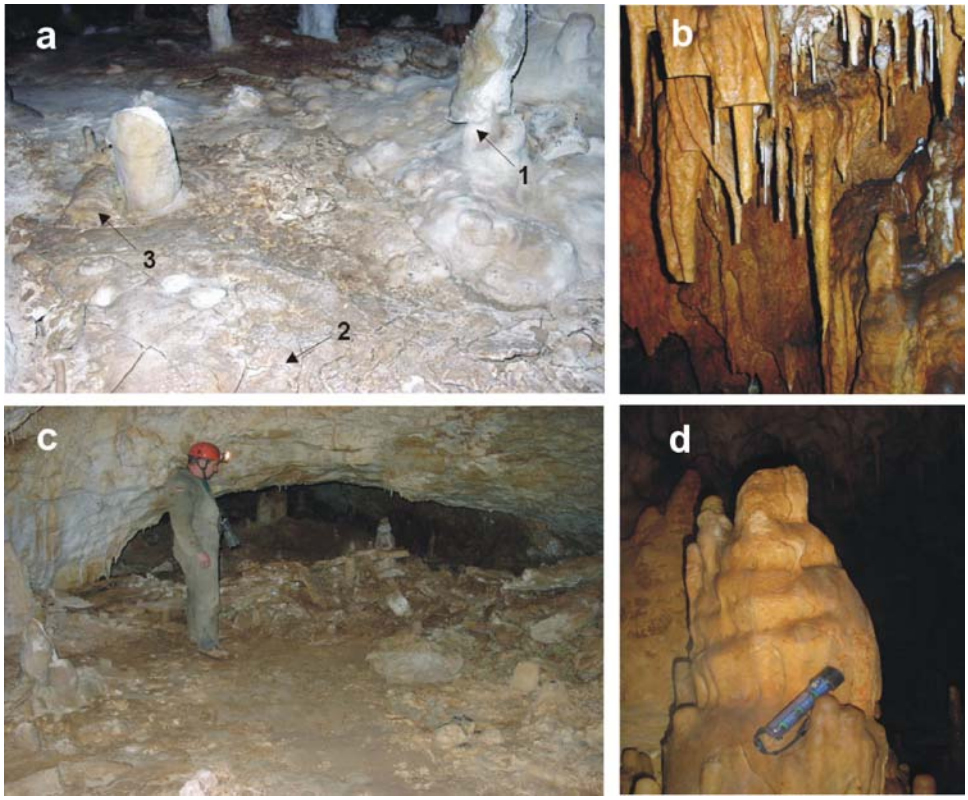

Fig. 7 (a) Broken stalagmite in Geisloch cave, Germany, with the top still on the stump but slightly displaced to the left with the fracture partly covered with younger coatings [1], old flowstone broken into polygonal fragments [2], whereas the younger flowstone is unbroken around [1]. A broken and embedded stalagmite fragment can be seen at [3]. (b) Stalactite stumps in Zoolithen cave, Germany, with unbroken stalactites close to the wall or behind larger stalactites (the soda straws are partly regrowths). (c) Stone wall in Geisloch cave, consisting of coarse material, mainly flowstone and speleothem fragments with bedrock from the surroundings, which has been interpreted as intra-cave glacial moraine (Spöcker, 1981). (d) A stalagmite partly-corroded by melt water trapped in the former marginal fissure between ice and speleothem in Geisloch cave, showing exposed layers on the left side [electric torch for scale].

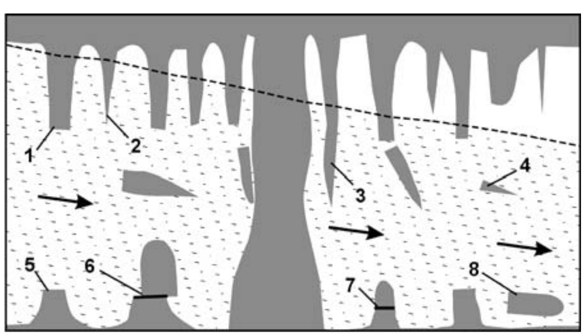

Fig. 8 Scheme modified after Gilli (1999a) showing the main effects of sediment movement or ice creep on speleothem formations: [1] stalactite stump, [2] unbroken stalactite protected by larger stalactites in the neighbourhood, [3] unbroken, thin and long stalactite protected behind a big column, [4] stalactite fragment embedded in sediment/ice oriented in the direction of mass flow, [5] stalagmite stump, [6] broken stalagmite with slightly laterally displaced cap, [7] broken stalagmite but still in position, [8] stalagmite fragment

sediment load will also have an impact on speleothems, particularly on such fragile formations as soda straws. Flood events with weak currents will not necessarily destroy speleothems. If such muddy water reaches stalactites and soda straws at the cave's ceiling, they will be coated by mud. Hence floods can be recognized in caves by a coating of clay and silt on walls and speleothems.

Frost action

Close to the entrance of caves and in cave sections close to the Earth's surface – so-called subcutaneous caves – and in so-called 'ice caves', frost shattering and weathering due to freeze-thaw pressures and accumulation of ice in fractures and along bedding plains can cause severe damage to rock and cave deposits. A characteristic feature of gelifraction is the accumulation of rock fall debris on the cave floor consisting mainly of coarse angular components similar to scree (Bögli, 1978; Schmid, 1958).

Decompression, load and slope movements

Rock decompression that affects caves when they are close to the surface is another important cause of destruction. The opening of cracks may break the flowstone that covers the walls. On the other hand, highly stressed pillars or thin walls separating neighbouring cave sections can fail under the load of the overburden rock mass causing cracking and spalling of the rock and speleothems (Gilli 1986, 2004).

Slope movements are an important cave forming process, generating "slope tectonic caves" simply by the opening of fractures by valley-ward movements of rock slabs. Also many caves formed by rock corrosion can, at some stage in their evolution, come close to the Earth's surface in steep terrains or at cliff sites and become involved in slope movements. Such caves in unstable slopes can be outstanding recorders for long-term slope movements, particularly where seen in speleothem growth anomalies (Gilli, 1995b). However, slope movements can find their expressions in caves by slip along bedding planes, opening of fractures, reactivation of faults and tilting of the cave's floor, which could be misinterpreted as expressions of active tectonics or strong ground shaking. The use of such caves for paleoseismic studies has to be based on a very careful analysis of the local situation to avoid misinterpretations.

Sediment deformations

Clastic deposits are widespread in caves. Investigations often involve trenching, which can be very difficult in narrow cave passages. It may happen that a stream cuts into the deposits, generating a freely accessible outcrop. Such ideal conditions were met in the Sous-les-Sangles Cave in the southern Jura Mountains, permitting the detailed analysis of late Pleistocene deposits, particularly for traces of strong earthquake shocks (Lignier and Desmet, 2002). Most interesting are the laminated ('varved') fine-grained silty sandy layers, which were deposited in a low-energy sedimentary environment (Fig. 9). Small scale faults with minor offsets and slumps can be easily recognized in such deposits (Fig. 10a). In addition, such sediments, when kept in water saturated conditions, are susceptible to liquefaction under the influence of strong ground motions (Fig. 10 b,c). Similar sedimentary conditions and earthquake-induced soft sediment structures in fine-laminated lacustrine deposits have been described for the late Quaternary (Monecke et al., 2004; Ringrose, 1987). The deformation of such sediments permit estimates of the required earthquake intensities (Davenport, 1994; Rodriguez-Pascua et al., 2000), which could equally be applied to similar deformation features in caves. However, interpretations in caves are complicated by "site and tunnel" response effects.

In using sediment deformation, it is necessary to distinguish between (i) those deformations which were generated syn-depositional or shortly after their deposition (i.e. early diagenesis) in an environment which still closely reflects the situation during the sedimentation and (ii) those which were generated long after the sedimentation. In the first case (i), deformations take place in an aqueous environment most likely in a flooded cave section with weak water currents. The deformations seen in the sediments are thus the expression of shear failure or liquefaction, which can be caused, for instance, by small scale slope instabilities (sub-aqueous sliding), rapid lowering of the water table or seismic shocks. In the second case (ii), deformations take place in a sub-aerial environment, even in dry sediments. These are predominantly brittle deformations.

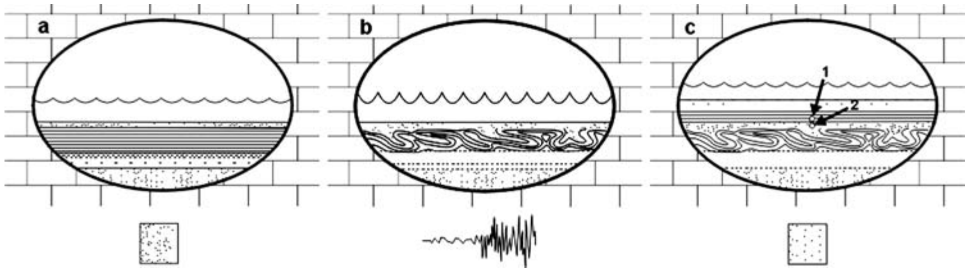

Fig. 9 (a) In an aqueous cave environment with low flow velocities, fine grained sediments will be deposited, which are in cases finely laminated. (b) An earthquake may trigger soft-sediment deformations caused by liquefaction. (c) Dating of the undisturbed sediments immediately above the event horizon (1) post-dates the seismic event. If the top-layer of the event horizon is only mildly disturbed, the sample (2) should immediately pre-date the event. Otherwise, a sample from the undisturbed layer immediately below the event horizon should be preferentially taken to approximately pre-date the event

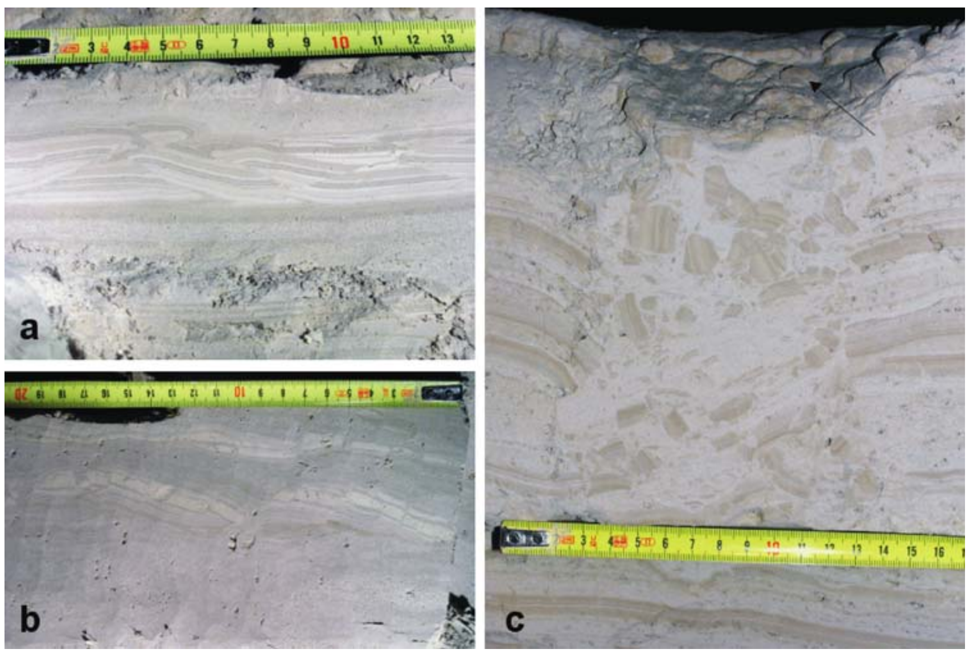

Fig. 10 Examples of soft-sediment deformation features from Sous-les-Sangles cave, France, with details given in Lignier and Desmet (2002): (a) small-scale thrusts caused by layer-parallel sliding, (b) liquefaction of a silty layer at the base causes the break-up and subsidence of the overlying weakly lithified layer, (c) a dewatering canal created by liquefaction within finely laminated silty sediments. Large layer fragments are embedded in a homogeneous matrix, with fragments also deposited at the surface (arrow). Note the downward bending of layers at the margin of the vent and the lowermost layer, which is unbroken

Although it cannot be excluded that these deformation features are triggered by strong earthquake shocks, they are most likely the expression of sediment compaction or long-term movements along fractures.

Incasion and slope Instabilities

The term 'incasion' describes cave instabilities which may find their expression in single rock falls or the collapse of whole cave sections. It is well known from outside the cave archive that earthquakes can trigger rock falls (Becker and Davenport, 2003; Keefer, 1984). Most interesting for paleoseismic research are those sites which are largely stable and where only unusual events, such as earthquakes, may trigger rock falls. The same is true for the cave archive (Fig. 11): only sites which are not particularly unstable are interesting for such kind of investigations. Becker (1929), when reflecting on the possibility that earthquakes may damage caves, described an incasion in the Pappenheim cave in

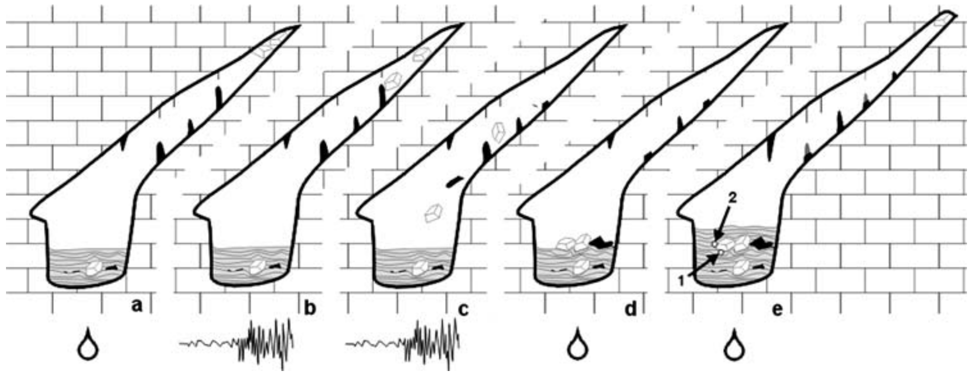

Fig. 11 In a cave which is not particularly unstable (a), rock falls (incasion) triggered by earthquakes may be rare events (b). Such rock falls may damage speleothems (c), and the fragments, together with the rock fall blocks, may rest on sediments (d). Finally, the debris will be embedded in sediments and regrowth will form on top of speleothem stumps (e). Dating of the event is possible either by sampling the broken stalagmites (cf. Fig. 1) or by sampling the sediments below the event horizon (1) and above (2), respectively

the Franconian Jura, which he related to the "AD 1356 Rothenburg earthquake". Although such an earthquake is now believed not to exist, the damage in Rothenburg is attributed to the MSK (or EMS) IX-X AD 1356 Basle earthquake (Mayer-Rosa and Cardiot, 1979). Becker (1929) seems to have described a far-field effect of the Basle earthquake in an area that experienced a MSK intensity around VI. After Becker's 1929 publication, incasion was rarely used as a possible indicator for past earthquakes (Kagan et al., 2005; Lemeille et al., 1999). An obstacle is the problem of dating single blocks and establishing an unambiguous link with an earthquake. In the Pappenheim cave, Becker solved his dating problem using 13th to 14th century pottery, which he could find in the former cave floor and within the rock debris.

As described in Section 5.3.6, slope movement is an important cave forming process. This is particularly true in rapidly uplifting terrains with deeply incised river valleys like the Pyrenees or Alps. Most slope movements can be considered to be the expression of common slope degradation processes, as for instance in case of the Langenfeld cave (Kempe, 1989); however, in some cases these movements may also be caused by earthquakes, triggering rock falls, slumps, slides, debris avalanches ('sturzstroms') and mass flows (Jibson, 1996; Keefer, 1984). Earthquakes may not cause a complete failure of a slope but minor movements within the rock formation, which can be recognized (i) in the field by the opening of fissures behind cliff faces or minor displacements along pre-existing fractures and faults, and (ii) in caves by the slip along bedding planes, the opening of fractures generating fissures, the reactivation of faults causing normal or inverse displacements, and the tilting of a cave's floor. In such an environment, caves are often not suitable for paleoseismic studies due to persistent slope movements, their position near the Earth's surface or unfavourable speleothems. However, where they are suitable, they may provide an outstanding record of earthquake-triggered slope movements. In any case, a careful analysis of the local geological situation is important to recognize the processes which caused the observed displacement in the cave.

Seismogenic faults in caves

Many excellent examples for (non-slope) tectonic faults in caves are published (Bini et al., 1992; Gilli, 1986, 1996; Gilli and Delange, 1999; Gilli et al., 1999; Jeannin, 1990; Vandyke and Quinif, 2001), however, as to our knowledge, no seismogenic fault with co-seismic displacements has been discovered so far in caves. A possible candidate has been seen in Corredores cave, Ciudad Neilly, Costa Rica, described by Gilli (1995a), which, however, still awaits further investigations.

Dating of speleoseismic events

One of the most critical aspects of speleoseismological work and a difficult subject is the dating of events with appropriate accuracy. The dating has to show that destructions and deformations seen in different parts of the cave are synchronous (within the error bars of the

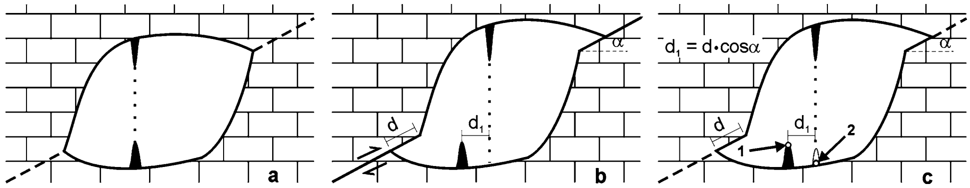

Fig. 12 Sudden displacements along pre-existing fault surfaces caused by co-seismic tectonic movements or slope instabilities may be responsible for an offset in the stalagmite-stalactite-system (a,b). After the displacement (b), the old stalagmite stops growing whilst a new stalagmite starts to grow some distance apart from the old one (c). When the dip (α) is known, the offset d_1 can be used to calculate the displacement on the fault. To date the event, samples can be taken from the top of the inactive stalagmite [1] and the base of the new stalagmite [2], which will respectively pre- and post-date the event

dating method) and belong to one seismic event. In this publication it is not possible to go into details of the difficulties involved with the methods used to date cave deposits (Eikenberg et al., 2001; Genty et al., 1999; Geyh and Schleicher, 1990; Ivanovich and Harmon, 1992; Kaufman, 1993; Kaufman et al., 1998). A variety of different dating methods are available, of which the most commonly used are the U/Th and the radiocarbon methods. All the dating methods have certain limitations and very often much effort is needed to accurately date speleothems and cave deposits. In some cases, a number of different methods need to be used just to identify the most suitable dating method to be applied in one single cave. Also a combined use of dating methods with stabile isotope analyses can help to significantly improve the dating accuracy for single paleoseismic events seen in broken speleothems (Kagan et al., 2005). Many problems with dating arise either by the nature of the cave environment itself, for instance due to (a) discontinuous sedimentation, (b) lack of organic material or (c) organic material that has been re-deposited, (d) open systems in an aqueous system causing leaching or contamination of datable material, or (e) incomplete knowledge about Earth's surface processes, e.g. unknown details about the climate and vegetation history as well as the soil formation.

Sampling sites for dating in case of broken speleothems have been described by Postpischl et al. (1991) in some detail and are also marked in Fig. 1. To bracket the event, the top layer of the fallen stalagmite has to be used and the oldest layer of the stalagmite regrowth. For stalactites, it is best to date the base and the top layer of the sediments where the fragments are embedded (Fig. 3c [1, 2]); most favourable being flowstones (Gilli, 1999b). The same is true for incasion blocks resting on sediments: a sample should be taken directly from the top layer on which the block rests and the oldest layer on top of the block (Fig. 11e [1, 2]), for instance the basal layer of a stalagmite growing on top of the incasion block (Kagan et al., 2005). In cases of soft sediment deformation features, one should try to date the oldest layer on top of the deformed horizon which just post-dates the deformation event (Fig. 9c [2, 1]). For growth anomalies, the layers which just pre- and post-date the event should be dated (Fig. 2b,c [1, 2]). The same is true in cases of the fracturing of speleothems; most important in this case is the top-sample which post-dates the fracturing event and another sample from the layer just below the undisturbed top-layer still containing fractures.

Even if it is not possible to date the damaging event(s) in the cave archive with high accuracy, this information at least gives an indication about timing. Strong earthquakes should be expected to not only leave traces in the cave archive but also leave stronger evidence in surface geological archives such as lake deposits, active faults or cliff sites. If an event seen in the cave archive can be dated only with large error bars, it may be possible to improve the estimate based on evidence seen in the geological archives outside the cave archive (Becker et al., 2005; Kagan et al., 2005).

Discussion

Caves are a 'micro-cosmos' which can cover all surface archives commonly used in paleoseismological research e.g. active faults, rock falls and slope instabilities, sediment deformations. In addition there are archives which are exclusively developed in caves and are mainly related to the growth and damage of speleothems (Forti, 2001). The decision that an earthquake caused deformations and damage in a cave should not be taken before alternative explanations have been excluded. Broken speleothems in unusual positions, long broken pieces of fragile soda straws on the cave's floor, remnants of sediments at the cave wall or in niches, corrosively-enlarged fracture traces in the cave's roof may all point to a former massive sedimentary infill of the cave. Ice may also break flowstone layers and speleothems, remove coatings from the cave walls, also bring broken speleothems into unusual positions, form moraine deposits and, together with melt-water, characteristically corrode cave rock walls, stalagmites and coatings. A flood, if not completely disastrous for the speleothems, may be indicated by thin fine-grained sedimentary layers embedded in various speleothems. Also the effects of slow movements along bedding and (non-seismogenic) fault planes have to be excluded as possible indications of former earthquakes. In a case where all non-seismic trigger mechanisms for the observed deformations and destructions can be excluded, the question whether an earthquake caused the damages seen in the cave is best resolved by the (i) comparison with observations from neighbouring caves, (ii) investigation of geological archives outside the cave archive, and (iii) the careful dating. This is because strong earthquakes should not only leave traces in one cave, they should leave traces in a number of caves in the epicentral area in addition to stronger evidence in surface geological archives such as lake and flood-plain deposits, cliff sites or active fau lts.

Conclusions

Based on what is known from tunnel engineering, underground cavities are expected to be very stable during earthquake shaking. This view is supported by the observations of eye-witnesses in caves, which rarely report damage triggered by earthquakes. However, caves close to the Earth's surface and topographically exposed positions may suffer from strong earthquake shocks, as reported by speleologists who visited such caves shortly after strong earthquakes. Progress in speleology during the last decade has increased the possibility of recognizing the causes of non-seismic cave damage. Laboratory and field experiments show that most speleothems are quite robust and most of them can resist earthquake shocks. Most sensitive are soda straws, which can break directly due to earthquake shaking. Although it seems that the cave archive is losing its potential to be a powerful tool in paleoseismology, we believe that this is not the case. Speleothems are only one of the potentially vulnerable features in caves. A particularly interesting class of cave deposits display signs of soft-sediment deformation caused by earthquakes. Also rock falls and related deposits in caves, as well as the effects of instabilities of slopes containing caves – which may cause displacements along bedding plains, pre-existing faults and the tilting of whole cave sections – could be valuable in paleoseismic studies. We believe that it is important to widen the view on the cave archive, not only speleothems but all the cave phenomena which are part of a complex geological environment.

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